

A058744

NAVAL AIR PROPULSION CENTER  
TRENTON, NEW JERSEY 08628

PROPULSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

NAPC-PE-11

AUGUST 1978

PERFORMANCE OF HOT FUEL IN A SINGLE TUBE  
HEAT EXCHANGER TEST RIG

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AUTHORIZATION: NAVAIR AIRTASK NO. A5365360-052F-6WSL700000  
WORK UNIT PLAN NO. NAPTC-4R6-711, 15 JULY 1975

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER <b>14</b> NAPC-PE-11	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER <b>9</b>
4. TITLE (and Subtitle) <b>6</b> Performance of Hot Fuel In A Single Tube Heat Exchanger Test Rig	5. TYPE OF REPORT & PERIOD COVERED Final <i>rept.</i>	
7. AUTHOR <b>10</b> Raymonu J. Delfosse	8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Air Propulsion Center Fuels and Fluid Systems Division (PE71) Trenton, New Jersey 08628	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 25662N WSL70,080 NAPTC 4R6 711	
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command (ATR-5364C) Washington, DC 20361	12. REPORT DATE <b>11</b> August 1979	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) <b>12</b> 31 P.	13. NUMBER OF PAGES 28	
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release; Distribution Unlimited		18. SECURITY CLASS. (of this report)
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		18a. DECLASSIFICATION/DOWNGRADING SCHEDULE
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Aviation Fuel                      Copper Contamination Heat Exchangers Gas Turbine Engines Heat Transfer Thermal Stability		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A single tube heat exchanger test rig was utilized to establish the effects of fuel heating upon fuel degradation. Fuel degradation effects were determined by weighing fuel deposits within the heat exchanger tube and measuring the change in heat exchanger effectiveness ratio. Fuels of varying thermal oxidative stability characteristics were tested and a relationship was developed between those characteristics and the performance of the fuels in the heat exchanger rig.		

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S/N 0102-014-6601

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420 500

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CONVERSION FACTORS: SI TO U.S. CUSTOMARY UNITS

<u>Convert From</u>	<u>To</u>	<u>Multiply by</u>
degree Celsius (°C)	degree Fahrenheit (°F)	$t_{°F} = 1.8 t_{°C} + 32$
kilogram (kg)	pound (lb)	2.204 622
litre	gallon (gal.)	$2.641\ 728 \times 10^{-1}$
pascal (Pa)	pound per square inch (psi)	$1.450\ 377 \times 10^{-4}$

## INTRODUCTION

The thermal oxidation stability of JP-5 is controlled by the D-3241 test method and specified limits contained in Specification MIL-T-5624K. This test method is empirical and does not represent any specific engine/aircraft condition. Past experience has shown that the current level of thermal oxidation stability has successfully prevented engine fuel system deposition problems due to thermal instability. At the same time, the engine manufacturer has taken this factor into consideration in the fuel system design. However, the trend in engine fuel temperature is up and there is a possibility the fuels of the future with broadened requirements will have lower oxidation stability. It is therefore necessary to establish relationships between fuel thermal oxidation characteristics and fuel performance in critical fuel system components, in order to more closely define the actual requirements of the engine hardware. Only with such information can design, performance and cost trade-offs be evaluated.

Improvements in the testing of jet fuels to establish their thermal oxidative stability characteristics continue to be explored. Current tests are of an accelerated nature due to the practical demands of time and sample size. However, these tests elude the definition of thermal oxidative stability in the strict sense of what is actually required of a fuel in an aircraft operating regime.

The effort under this Work Unit Assignment tried to approach more closely the heat exchange process in aircraft, where fuel is used to cool the engine lubricating oil. By scaling down the installation to laboratory or bench dimensions, the general effects of heat on fuel in a heat exchanger situation, over a long period of time, were observed. At sufficiently high operating temperatures, fuel deposits form within the heat exchanger tubes, and cause heat transfer changes. Some correlation between the two types of testing, long-term and accelerated, should offer a way to add a time-prediction factor to fuel breakdown criteria: a heat exchanger breakpoint (time for specific decrease in effectiveness to occur) relative to the jet fuel thermal oxidation tester (JFTOT) breakpoint temperature for one.

The Navy is interested in the general effects of JP-5 fuels of varied thermal stability in jet aircraft fuel systems particularly because of the copper contamination of JP-5 that occurs on board aircraft carriers. This copper contamination situation is unique to the Navy and causes the thermal oxidative stability characteristics of JP-5 to degrade.

This Work Unit Assignment was authorized by reference 1.

## CONCLUSIONS

1. There is a trend for the fuels to cause deterioration of heat exchanger performance in the order of their thermal stability threshold temperature ratings as determined by the JFTOT.
2. A more reliable and realistic quantitative determination of the

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relationships between fuel thermal stability and heat exchanger performance could not be made because of limitations in the sensitivity and stability of the test devices.

3. A fuel with a high natural copper content can cause a blocking condition (due to deposition) in the heat exchanger tube in a relatively short time.
4. Copper contamination in fuel is prone to precipitate at the first heated surface of contact, with accumulation of the deposits downstream.
5. Physical examination of heat exchanger tube fouling reveals patterns of downstream accumulation and agglomeration of particles.

#### RECOMMENDATIONS

1. Additional work on heat exchanger performance of fuels should be done with:
  - a. a larger variety of different fuels at the same temperature, and in replicate.
  - b. similar fuels in replicate at different temperatures.
  - c. special fuels such as diesel fuel and shale oil derived fuels.
2. If further testing is done, the test rig and procedures should be modified for improved reliability and sensitivity. Tests should be run continuously and automatically.

#### DESCRIPTION OF TEST

1. The heat exchanger test equipment and test method were evolved during this test program. The control of the test and the data acquisition were performed manually at the beginning of the program. As the test program progressed, more sophisticated means were utilized to automate these processes thereby providing improved control of test conditions as well as permitting 24 hours per day of test operation vice eight hours per day. The description of the test provided in this section is that of the final more automated version.
2. Single Tube Heat Exchanger (HX) - Figure 1 is a schematic diagram of the test rig. JP-5 was pumped through the assembly consisting of a fuel preheater and a single aircraft HX tube from an F401 engine HX. In the HX rig, the fuel was heated by hot engine lubricating oil conforming to Military Specification MIL-L-23699B, Amendment 2, Lubricating Oil, Aircraft Turbine Engine, Synthetic Base. The oil flowed in the counter-flow direction to the fuel through a surrounding jacket. The fuel flow was once-through, while the lubricating oil was recirculated and inerted by sparging with nitrogen to prevent thermal oxidation. Flows of both fluids were metered, and the temperatures were maintained at prescribed values. Figure 2 is a

schematic view of the test section and shows the fuel and oil passages. Semi-circular baffles are attached to the fuel heat exchanger tube. The baffles are evenly located along the tube to prevent the tube from distorting during heating and to produce lube oil turbulence for even heating of the fuel. Figure 3 shows the thermocouple locations in the rig.

3. Temperature Control and Data Recording - Figure 4 shows the arrangement of the temperature control unit, the lube heater and the data recorder, which are required to achieve automation and uninterrupted running. Constant fuel temperatures are maintained throughout the test. As deposits form on the fuel side of the HX tube, the fuel out temperature will tend to decrease. Any deviation in the HX fuel out temperature is sensed by the controller which signals the lube heater to make an adjustment in the lube-in temperature. All temperatures across the HX including the fuel preheater are digitally recorded at specific intervals. The data is manually fed into the computer and stored.

4. Calculation of HX Effectiveness Coefficient - The HX effectiveness coefficient ( $\epsilon$ ) is calculated from the fuel and lube temperatures and plotted as a function of time. The deterioration or the decay in the  $\epsilon$  value is a measure of deposit formation in the HX. To simplify the calculations and the interpretation of the data, the only variable in the equation is the lube-in temperature. The fuel-in and out temperatures as mentioned earlier are maintained constant. The HX  $\epsilon$  equation is as follows:

$$\epsilon = \frac{T_{f_o} - T_{f_i}}{T_{l_i} - T_{f_i}}$$

Where:  $\epsilon$  = heat exchanger effectiveness coefficient

$T_{f_i}$  = temperature of fuel in (constant)

$T_{f_o}$  = temperature of fuel out (constant)

$T_{l_i}$  = temperature of lube in (variable)

5. JP-5 Test Fuels - Four fuels of different thermal oxidation stability were studied. The breakpoint temperatures of the fuels were adjusted by two methods, (1) adding a copper organic complex and (2) exposing a fuel to copper specimens. Fuel B, C, and D were prepared from the same batch of JP-5. It is important to note that fuel D had a lower breakpoint temperature than fuel C at the same copper concentration, which demonstrates that the type of soluble copper in the fuel has a pronounced effect on fuel stability. The thermal oxidative stability characteristics of the test fuels were determined by means of the ASTM D-3242 test method (Test for Thermal Oxidation Stability of Aviation Turbine Fuels (JTOT Procedure)). The breakpoint temperatures are those temperatures at which the fuel passes each of the two requirements contained in Specification MIL-T-5624K. The characteristics of the four fuels tested are as follows.



Fuel Designation	JFTOT BREAKPOINT TEMPERATURES, °C (°F)				Remarks
	Preheater		Pressure		
A	243	(470)	238	(460)	JP-5R + 50 ppb copper as bis (1-phenyl 1,3-butane-diono) copper II.
B	296	(565)	271	(520)	JP-5 + 50 ppb copper as bis (1-phenyl 1,3-butane-diono) copper II.
C	>249	(>480)	232	(450)	JP-5 + 250 ppb copper as bis (1-phenyl 1,3-butane-diono) copper II.
D	>223	(>433)	213	(416)	JP-5 + 250 ppb copper exposure to copper metal.

Copper concentrations in the fuel, derived from both organic additives and solution of copper metal, were determined with a Perkin-Elmer Model No. 403 Atomic Absorption Spectrophotometer.

6. Test Conditions - The four test fuels were subjected to the following conditions in the HX tests.

Fuel Designation	Fuel Temperatures, °C (°F)			Oil Temperatures, °C (°F)		
	Preheater Out	HX In	HX Out	HX In	HX Out	
A	149 (300)	136 (277)	188 (370)	210 (410)	199 (390)	
B	152 (305)	124 (256)	165 (329)	178 (353)	171 (339)	
B	135 (275)	126 (258)	170 (338)	186 (366)	173 (344)	
C	135 (275)	126 (258)	170 (338)	186 (366)	173 (344)	
D	135 (275)	126 (258)	170 (338)	186 (366)	173 (344)	

The fuel and oil flow rates were maintained constant throughout all the tests and were 1.62 liters/hour (0.428 gallons per hour) and 10.8 liters/hour (2.86 gallons per hour) respectively.

7. Detailed Description of Apparatus - For all runs the fuel was pumped from the fuel reservoir by a ZERO MAX variable speed pump with a ZENITH laboratory metering unit attachment. The fuel then passed through a 0.45 micrometer filter (Millipore Cellulosic) and a Fischer and Porter flowmeter, and then into a fuel preheater, taken from an ERDCO Fuel Coker Model 1FC-11. This

preheater was controlled automatically, after being manually set, by a Guardsman heat control unit (West Instrument Company). The preheated fuel then passed through the heat exchanger tube which was mounted inside a tubular heating jacket which was also obtained from an ERDCO Model IFC-11 fuel coker. The fuel then passed through a water cooled-fuel cooler (from the same ERDCO fuel coker), and finally into a waste drain. The heat exchanger and its inlet lines were heavily insulated with asbestos. The lubricating oil, which was used to heat the fuel in the heat exchanger, was pumped from an open reservoir. This reservoir, which contained two quarts of oil, also received the cooled returning oil and the oil flow could be manually checked at the reservoir. The sides of the reservoir were insulated, and nitrogen gas was bubbled through the oil to prevent it from deteriorating. The oil was pumped by a Graham metering pump, through a Fischer-Porter flow meter into the oil heater. The lube oil was heated by a Chromalox Circulation Heater (1500 watts, 120 volts, thermostated in the 66°C (150°F) to 288°C (550°F) range, with explosion resistant terminal cover). This oil heater was heavily insulated with asbestos. The thermocouples were the iron-constantan type. An electronic proportional heat controller (Thermo-electric Corporation, Model No. 321093302) sensed the operating temperatures and controlled them automatically. The data were printed out automatically by a Doric Digitrend 200 Printer Type J. This unit also had features to set minimum and maximum temperature limit signals, and to cut off power at a set overtemperature (Doric Selective Alarm Master Model 211A). The entire heater test section was set inside a laboratory hood vented at the top, to minimize ambient temperature changes, and to provide some safety control. There was a CO<sub>2</sub> fire extinguisher inside that could be actuated from the control section. The oil pump flow setting vernier could be adjusted by a long handle which extended through the front of the hood.

#### ANALYSIS OF RESULTS AND DISCUSSION

1. The results obtained with each of the test fuels are as follows:

a. Fuel A - The duration of this test was 280 hours. The  $\epsilon$  values obtained were plotted versus time and are shown on Figure 5. The fluctuations in the curve are the result of temperature control. For the purpose of observing trends in the curve, the  $\epsilon$  values were averaged over 12 hour periods. These averaged data are shown on Figure 6, along with a regression line calculated using all the data shown in Figure 5. The regression line was used to establish the time at which a one percent loss in  $\epsilon$  occurred. This value was 31 hours for fuel A.

b. Fuel B - The duration of this test was 600 hours. The averaged data (25 hour intervals) obtained for this fuel are shown in Figure 7 along with two regression lines. The initial 266 hours of operation showed a trend of increasing  $\epsilon$  with time. At 266 hours, the preheater fuel-out temperature was decreased to 135°C (275°F) and the HX fuel-in temperature was increased by 5°C in order to cause the data to show a decreasing  $\epsilon$  trend which did occur. Two regression lines were calculated. One represented the entire 600 hours of test and the other covered the range from 266 to 600 hours of test. For analysis purposes, the regression line covering the 266-600 hours was used. The initial 266 hours of operation were in effect ignored

because the condition was not severe enough to cause the desired degree of fuel deposition. The value of the one percent loss point was 107.3 hours (corresponds to 373.3 hours in Figure 7).

c. Fuel C - The duration of this run was 716 hours. The data obtained for this fuel (averaged at 30 hour intervals) are shown in Figure 8. Based on the regression line, a one percent loss in  $\epsilon$  occurred at 73 hours.

d. Fuel D - The duration of this run was 361 hours. This fuel was an extremely poor fuel (breakpoint temperature 213°C (415°F)). The fuel deposits produced by this fuel were so heavy that the heat exchanger was shut down twice to clean the thermocouples and unplug the fuel/water heat exchanger. The data obtained (averaged at 15 hour intervals) are shown on Figure 9 and a one percent loss in  $\epsilon$  occurred at 29 hours of operation.

2. A summary of the significant data are shown in Table I. On Figure 10, a plot is shown of the time for a one percent loss in  $\epsilon$  versus the JFTOT breakpoint temperature of the fuel. Two curves are shown which represent the two maximum fuel temperatures which were run during the HX tests. The curves indicate a reasonable trend of increasing time for a one percent loss in  $\epsilon$  as the fuel JFTOT breakpoint temperatures increase, for a constant maximum fuel temperature in the heat exchanger.

3. The amount of carbon deposition of the heat exchanger tube from the tests of fuels B, C and D was determined incrementally. These data are shown plotted in Figure 11. The data are useful to illustrate deposit formation patterns. For fuels B and C the deposits increase with increasing temperature along the tube. Fuel D however indicates the greatest deposits at the lower end of the tube which is unusual and may be related to the fact that this fuel had been subjected to copper metal. The total amount of carbon deposition on each heat exchanger tube was also determined. These data are shown in Table II. The data were normalized to parts per billion (ppb) of carbon for the total quantity of fuel used in each test and to deposit rate which takes into consideration the duration of each test. These data are also shown in Table II. On Figure 12, the deposit rate data are plotted versus the corresponding JFTOT breakpoint temperature of the fuel at the two heat exchanger maximum fuel temperature conditions. The two curves shown in Figure 12 show increasing deposit rate with decreasing fuel JFTOT breakpoint temperature which represents the trend anticipated.

4. As a final step in the analysis, a plot was made of deposit rate versus the corresponding time for a one percent loss in  $\epsilon$  to take place. This plot is shown in Figure 13 which indicates very good correlation between these factors (the greater the deposition rate the shorter the time for a one percent loss in  $\epsilon$  to take place).

5. Experience in testing fuels in the JFTOT has shown that fuels containing natural copper will normally have a lower breakpoint temperature for the pressure differential characteristic (which is indicative of solids generated in the fuel) than for the preheater rating characteristic (which is indicative of solids forming on the walls of tubing). However in the HX test of fuel D,

which contained natural copper, a heavy precipitate occurred which caused fouling and plugging of fuel lines.

6. Pertinent information regarding the conduct of each of the HX tests conducted in this program is contained in the following paragraphs. As changes were made to the test equipment/procedure, they were maintained in the tests that followed.

a. Fuel A - This test was conducted with manual control of the fuel-in and oil-in temperatures. The data were recorded manually, and the test was operated during one eight-hour shift per day.

b. Fuel B - An electronic proportional heat controller was added to maintain a constant 27°C (80°F) fuel temperature rise across the HX. This controller regulated the oil-in temperature to maintain the constant fuel temperature rise. After 280 hours of operation, the capability to record the data automatically at set time intervals was incorporated. This test was conducted during one eight-hour shift per day.

c. Fuel C - During this test, the test operation was shifted from one eight-hour shift per day to 24 hours per day for five days per week.

d. Fuel D - No changes were made during this test.

7. The effects of these changes noted in paragraph 6 are as follows:

a. With manual control of the test conditions, there were greater excursions from the test temperatures than occurred with automatic control.

b. Operating eight hours per day resulted in much more unrecorded operation (warm-up period at start and cool-down period at end of eight hour period) than occurred when operating 24 hours per day for five consecutive days.

c. Automated data recording eliminated any human errors involved in taking the data. The data were transferred to punch cards so that regression analysis could be performed by the computer.

8. Equipment failures occurred during this test program necessitating repairs which caused additional operation at non-test conditions. In several instances, fuel-in temperatures significantly exceeded the set test temperature for short periods (e.g. failure of maximum fuel-in temperature shut-off control). Both of these factors tended to increase the actual severity of segments of the test runs, and are a basis for not trying to analyze the data of segments of a test run, but rather to analyze the total test run in terms of its complete regression line. These factors also cause the correlation coefficients of the regression lines to be relatively poor, which could also be affected if the decrease in heat exchanger effectiveness with time is not a straight line function. The regression line correlation coefficients are shown in Table I.

FIGURE 1. TESTING RIG FLOW DIAGRAM

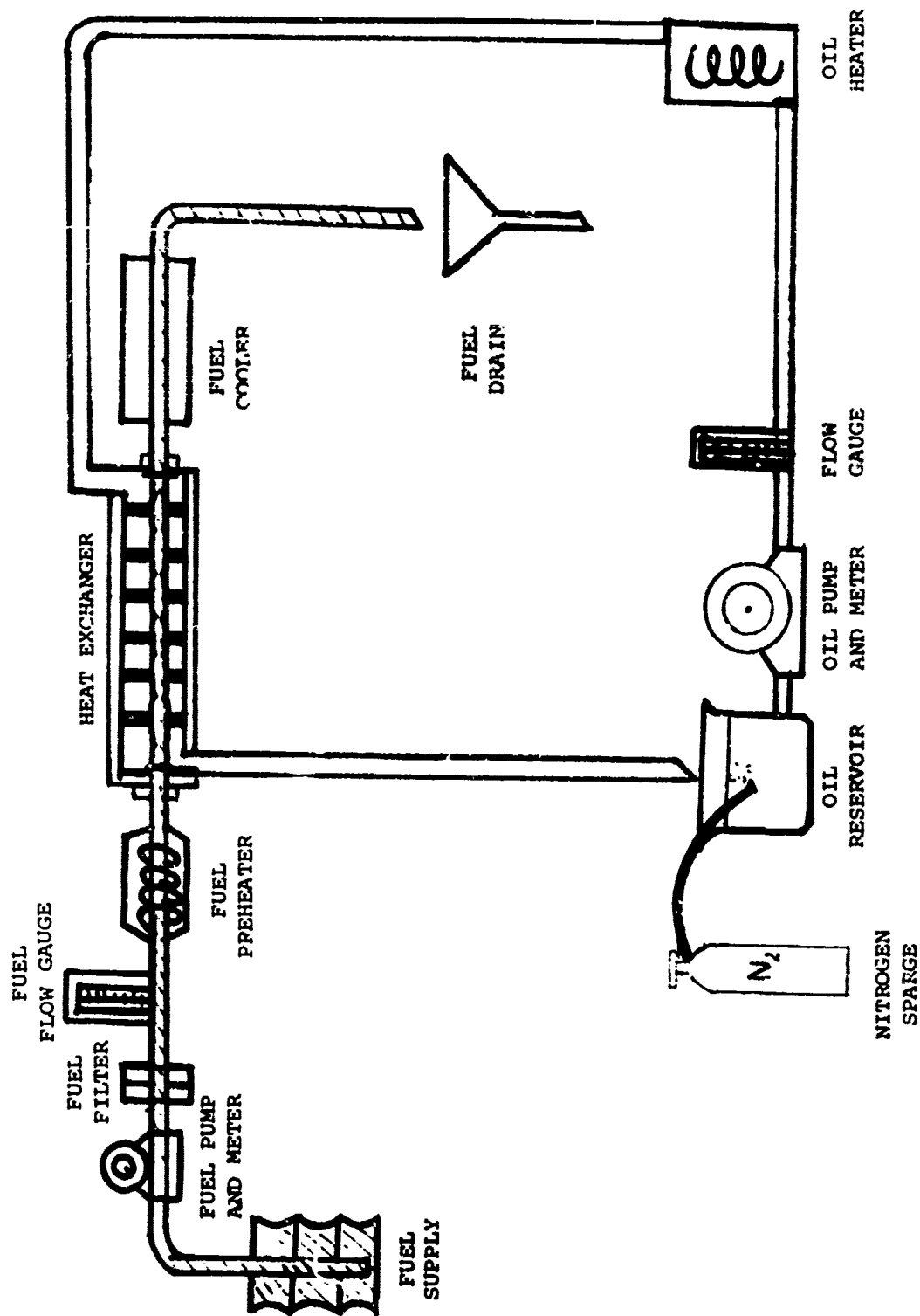


FIGURE 2. SCHEMATIC OF HX TEST SECTION

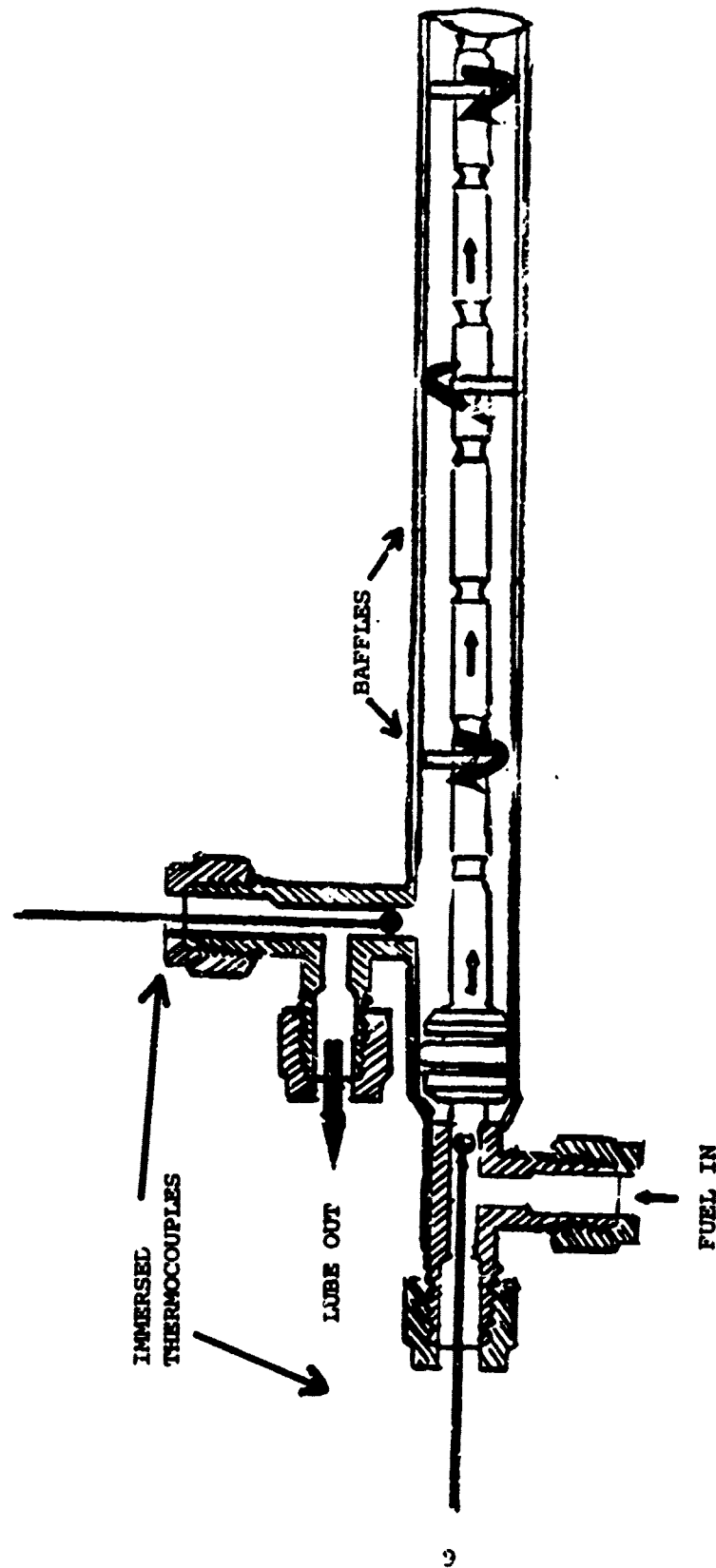


FIGURE 3. TESTING RIG THERMOCOUPLE LOCATIONS

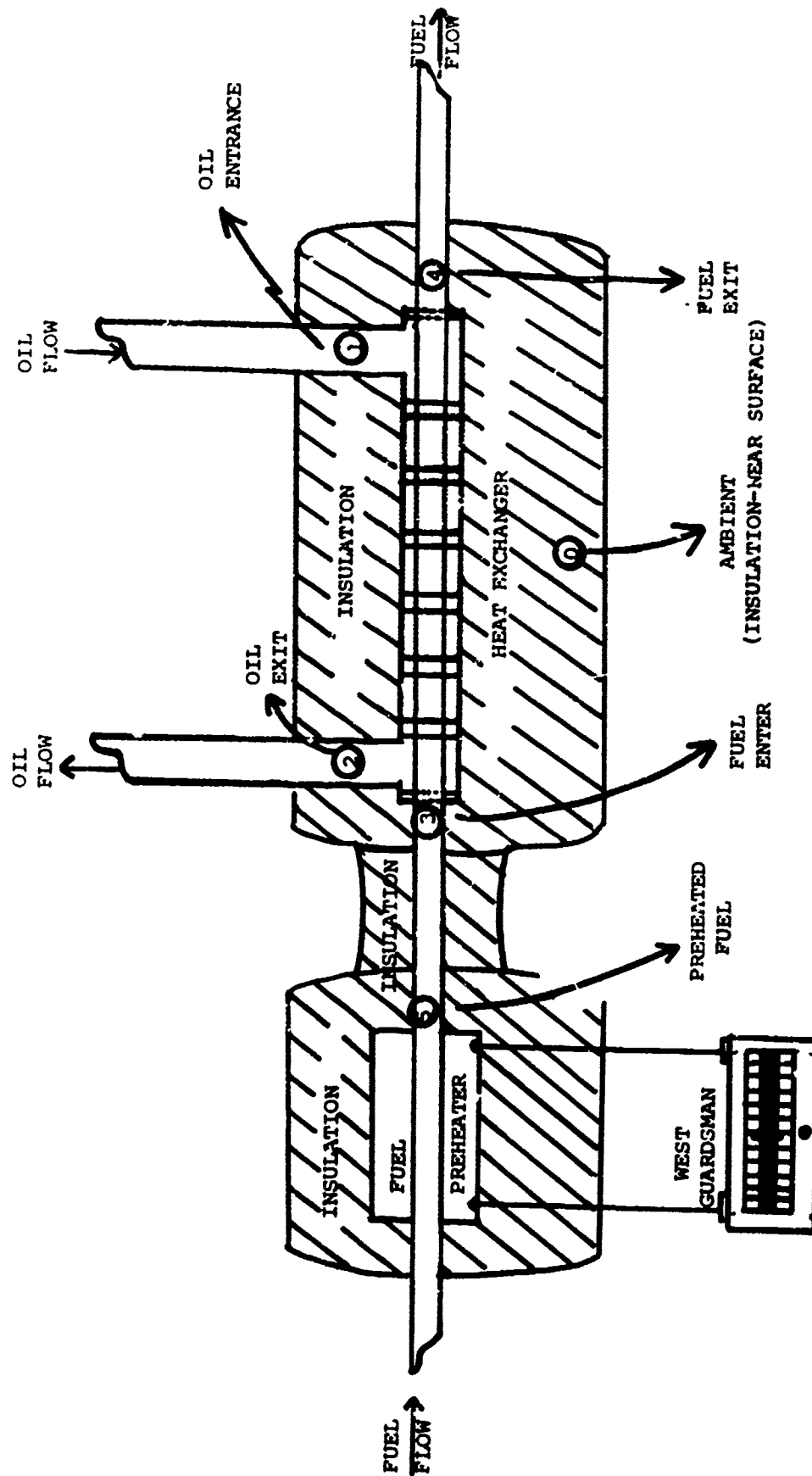


FIGURE 4. TEMPERATURE CONTROL AND RECORDING SYSTEM SCHEMATIC

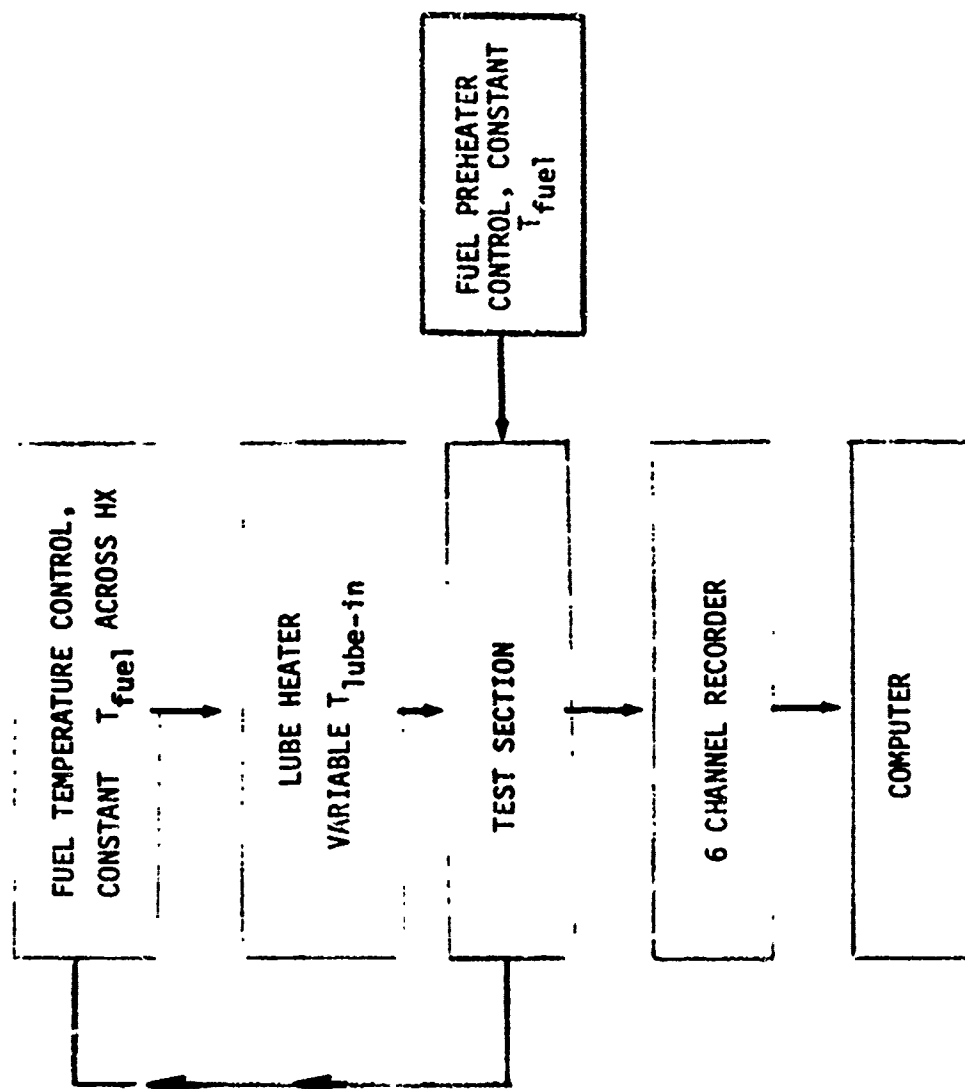




FIGURE 5. CHANGE IN  $\epsilon$  VERSUS TIME FOR FUEL A

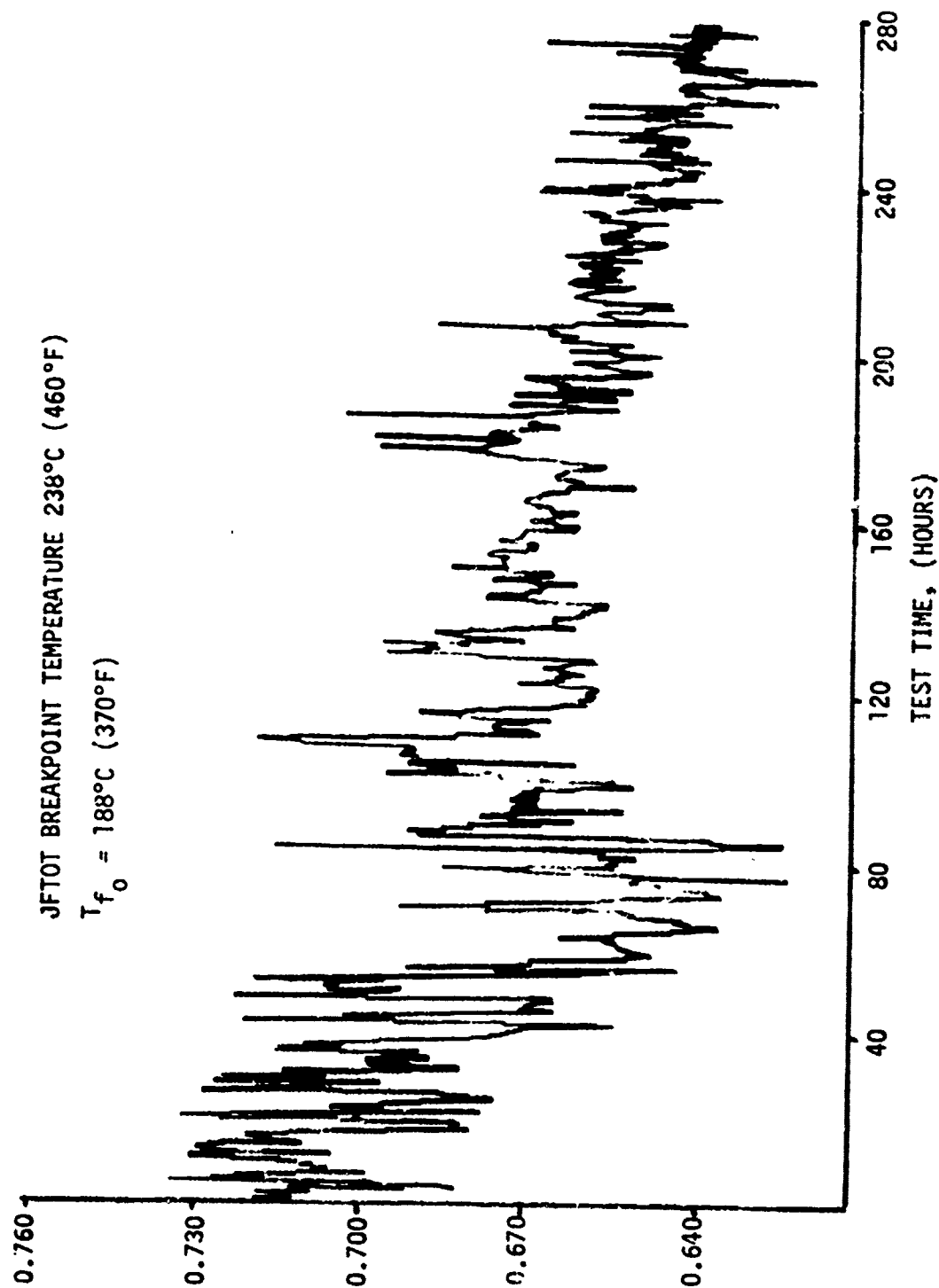


FIGURE 6. CHANGE IN  $\epsilon$  VERSUS TIME FOR FUEL A (AVERAGED DATA)

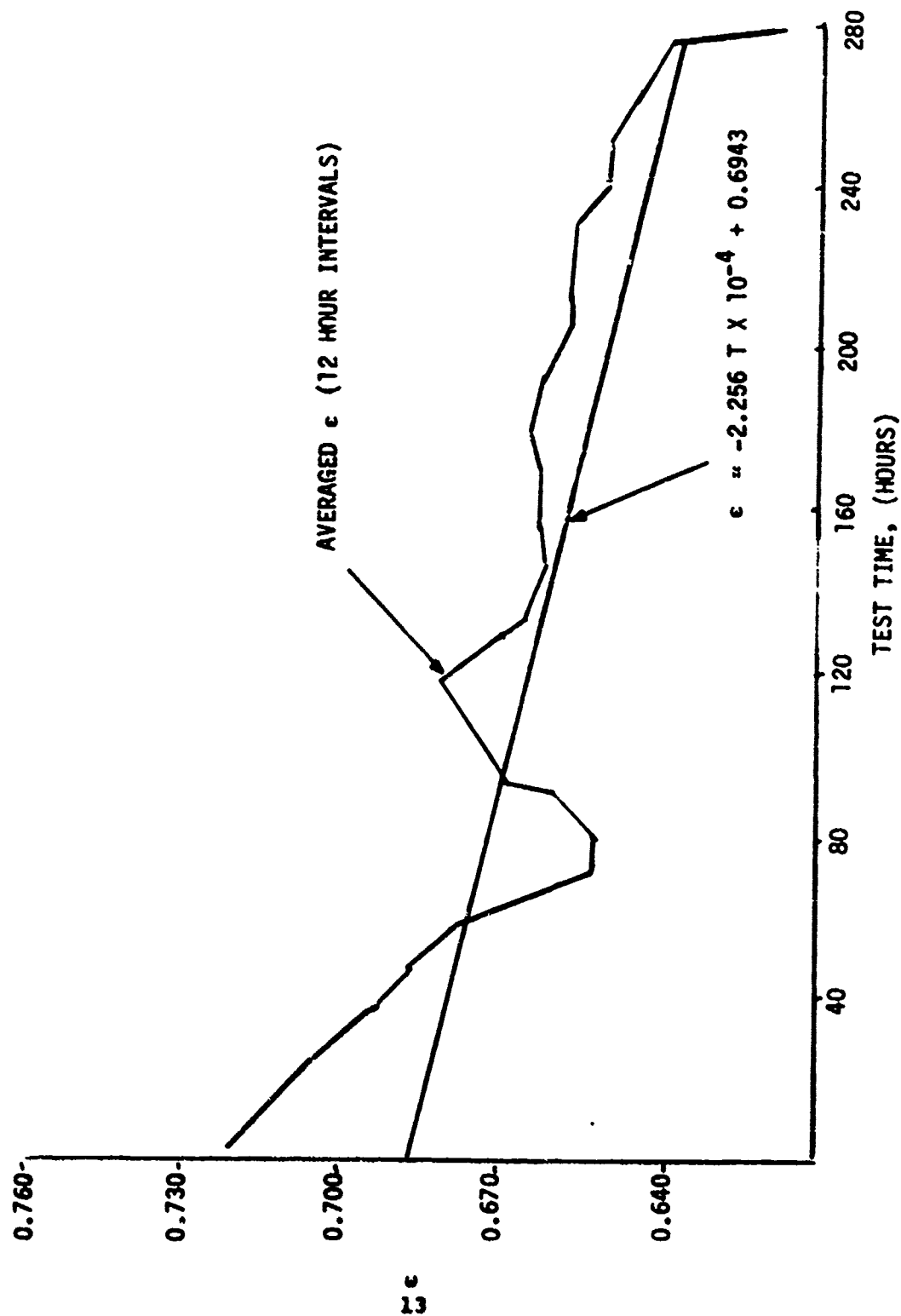


FIGURE 7. CHANGE IN  $\epsilon$  VERSUS TIME FOR FUEL B (AVERAGED DATA)

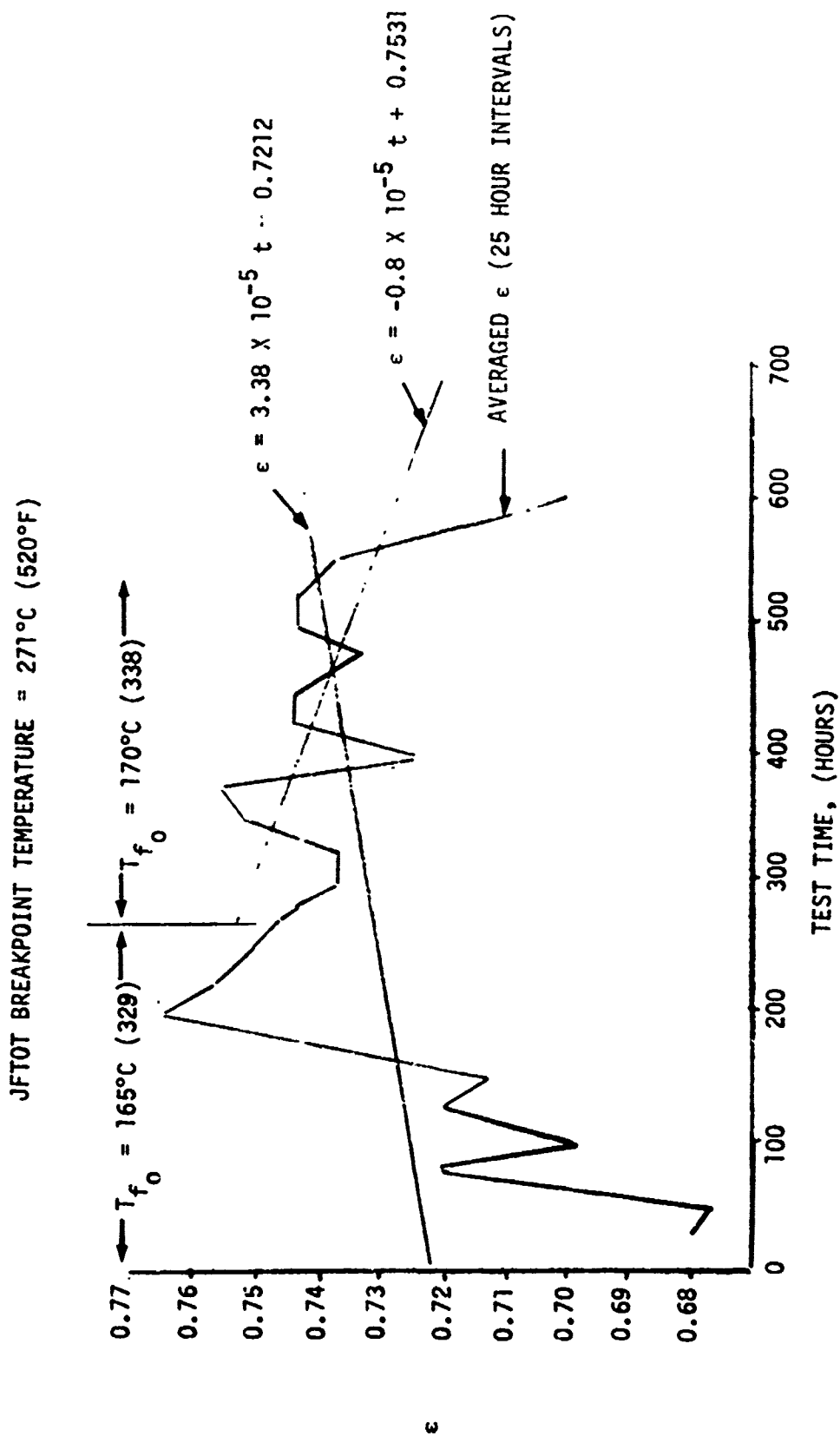


FIGURE 8. CHANGE IN  $\epsilon$  VERSUS TIME FOR FUEL C (AVERAGED DATA)

JFTOT BREAKPOINT TEMPERATURE = 232°C (450°F)

$T_{f_0} = 170^\circ\text{C} (338^\circ\text{F})$

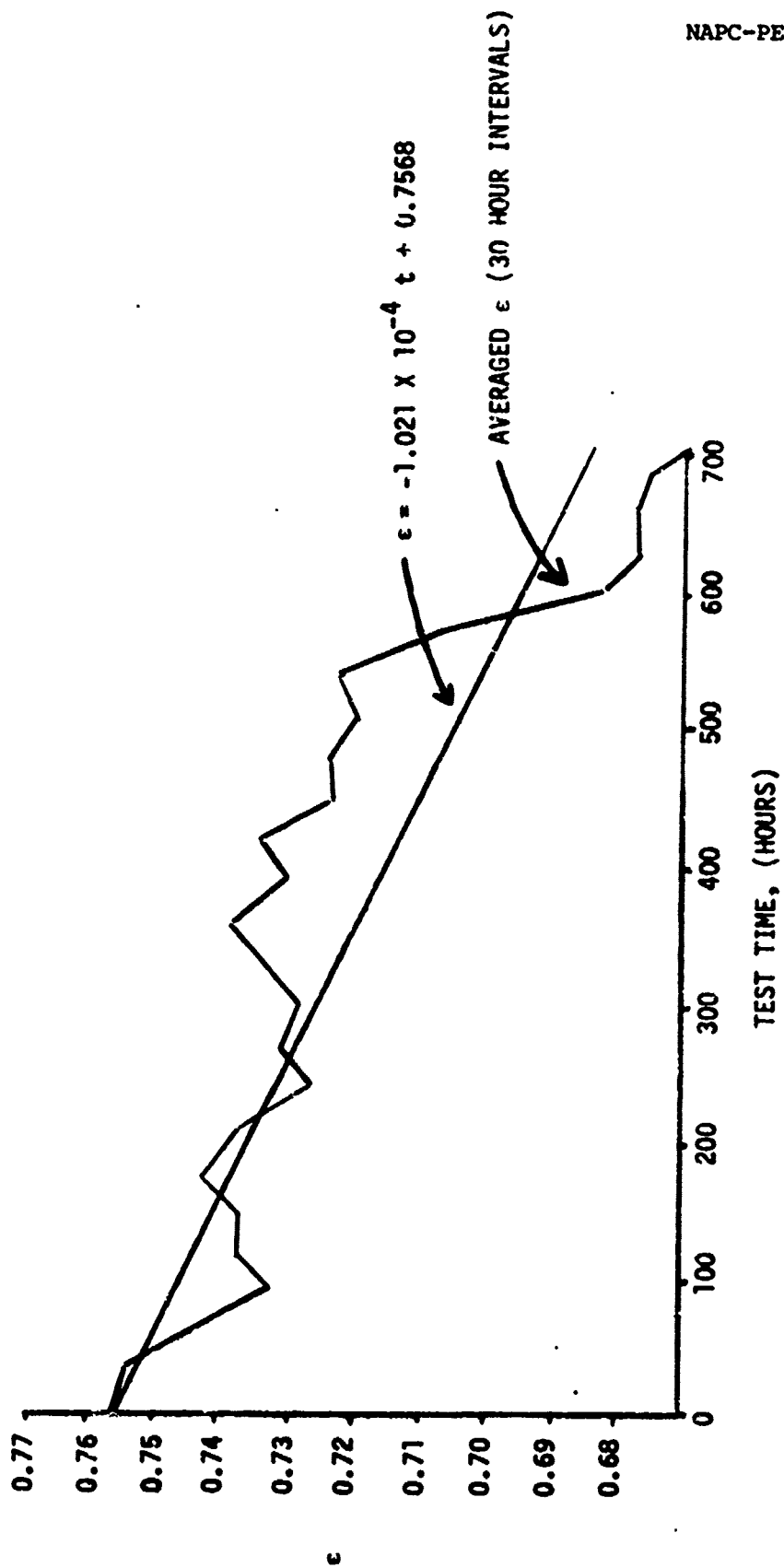


FIGURE 9. CHANGE IN  $\epsilon$  VERSUS TIME FOR FUEL D (AVERAGED DATA)

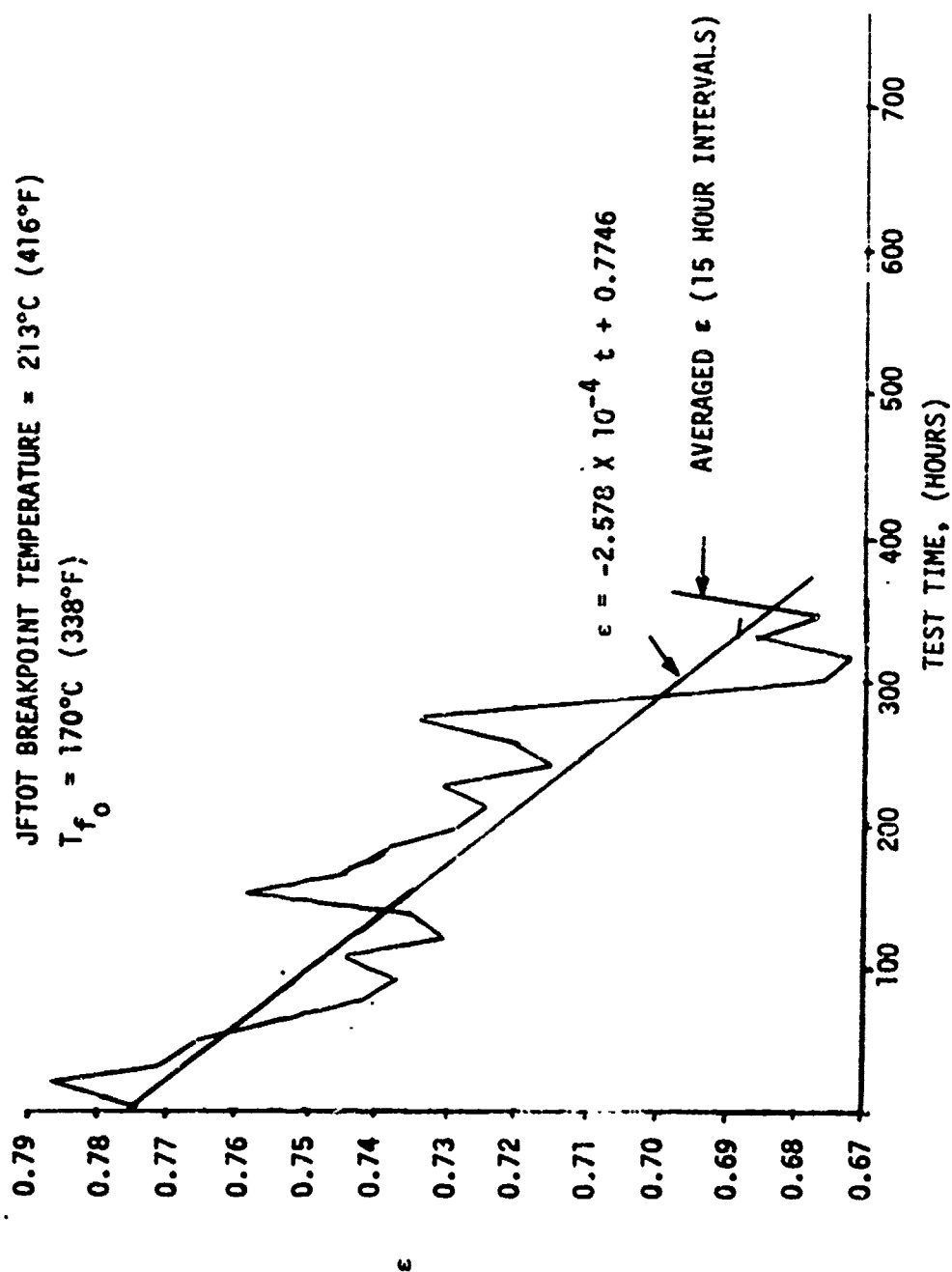


FIGURE 10. HOURS TO 1 PERCENT LOSS IN  $\epsilon$  VERSUS FUEL BREAKPOINT TEMPERATURE

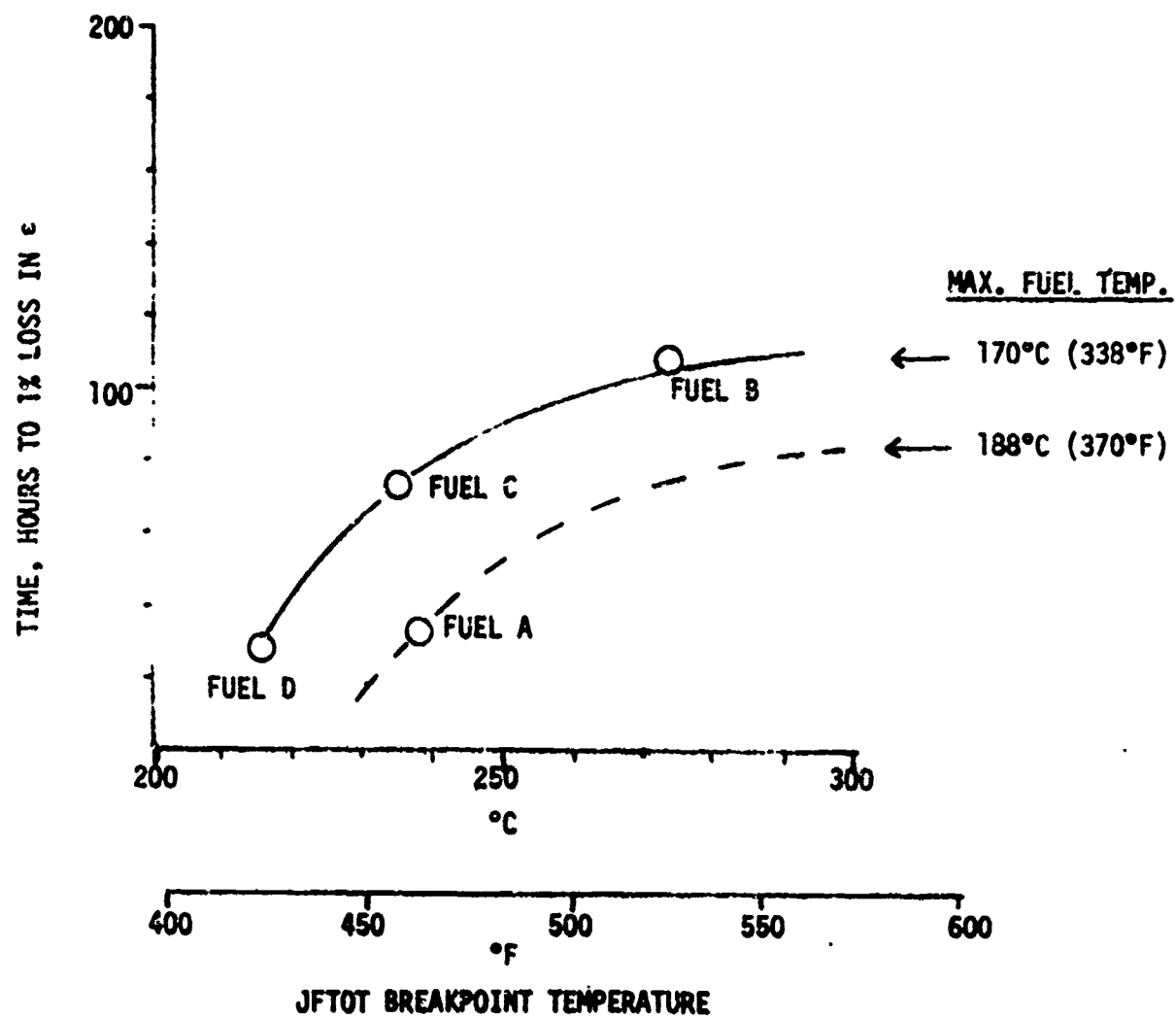


FIGURE 11. MICROGRAMS OF CARBON PER TUBE SECTION

(ANALYSIS PERFORMED BY NAVAL RESEARCH LABORATORY)

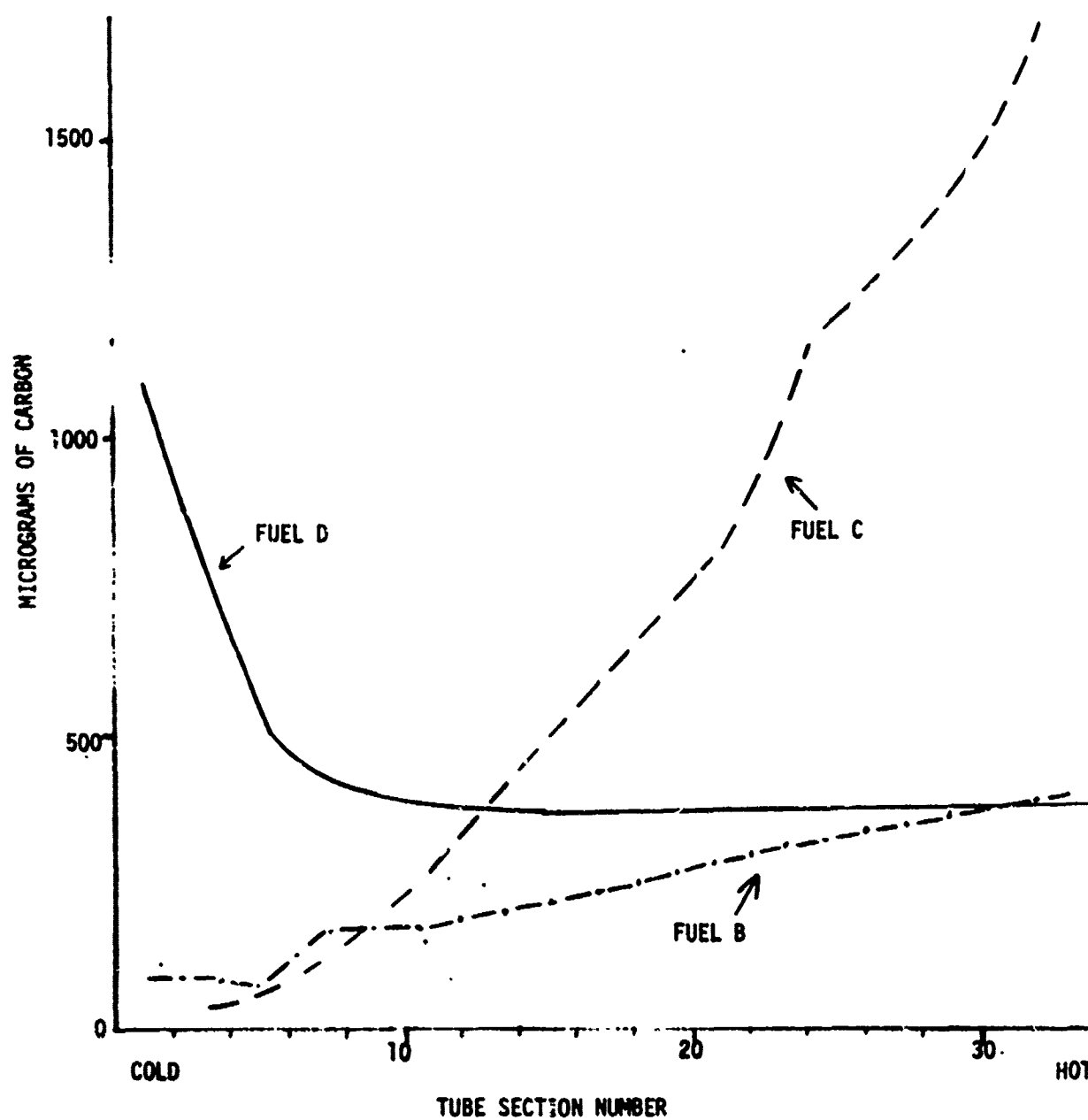


FIGURE 12. CARBON (C) DEPOSIT RATE VERSUS FUEL BREAKPOINT TEMPERATURE

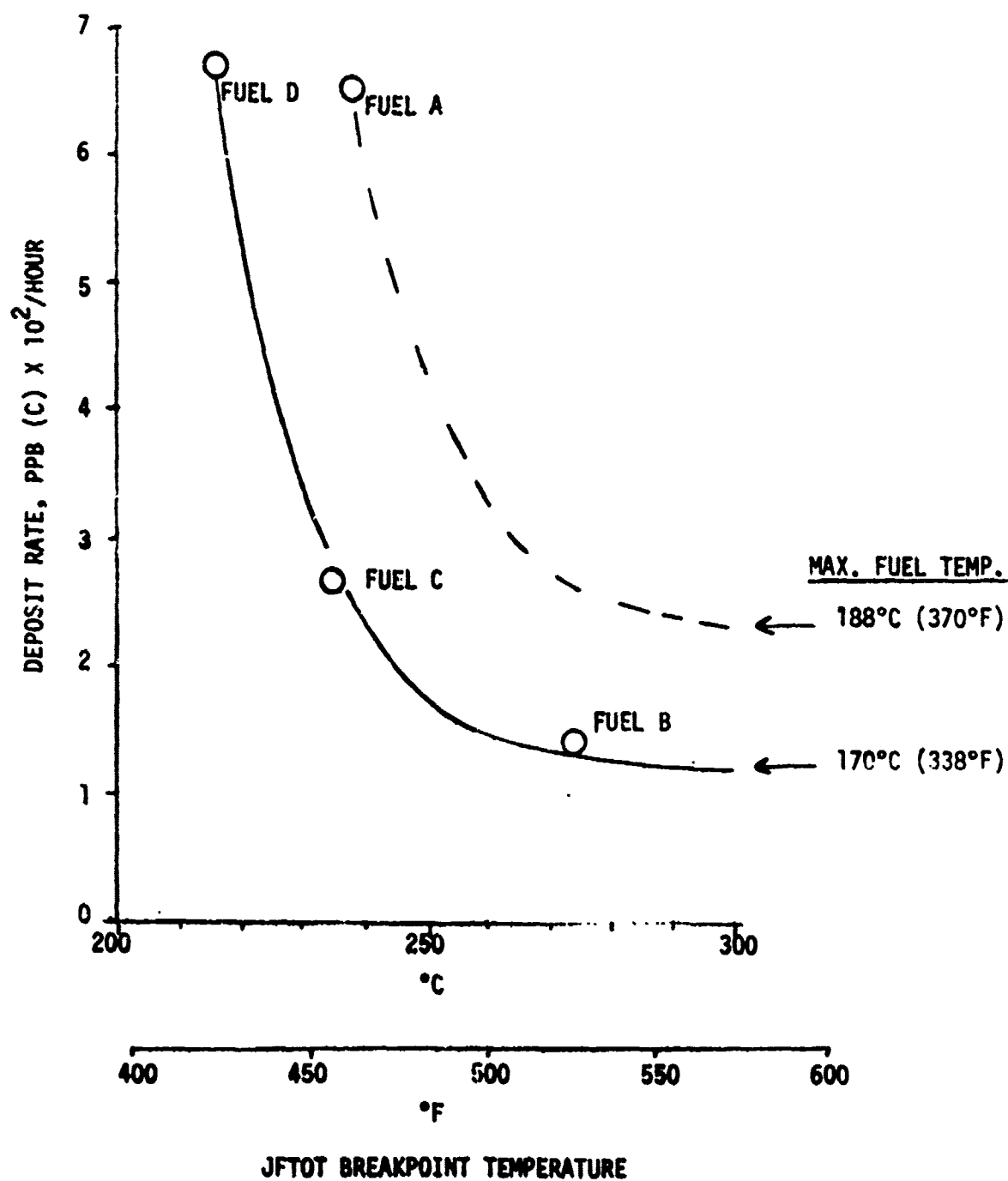




FIGURE 13. TIME TO 1 PERCENT LOSS IN  $\epsilon$  VERSUS DEPOSIT RATE

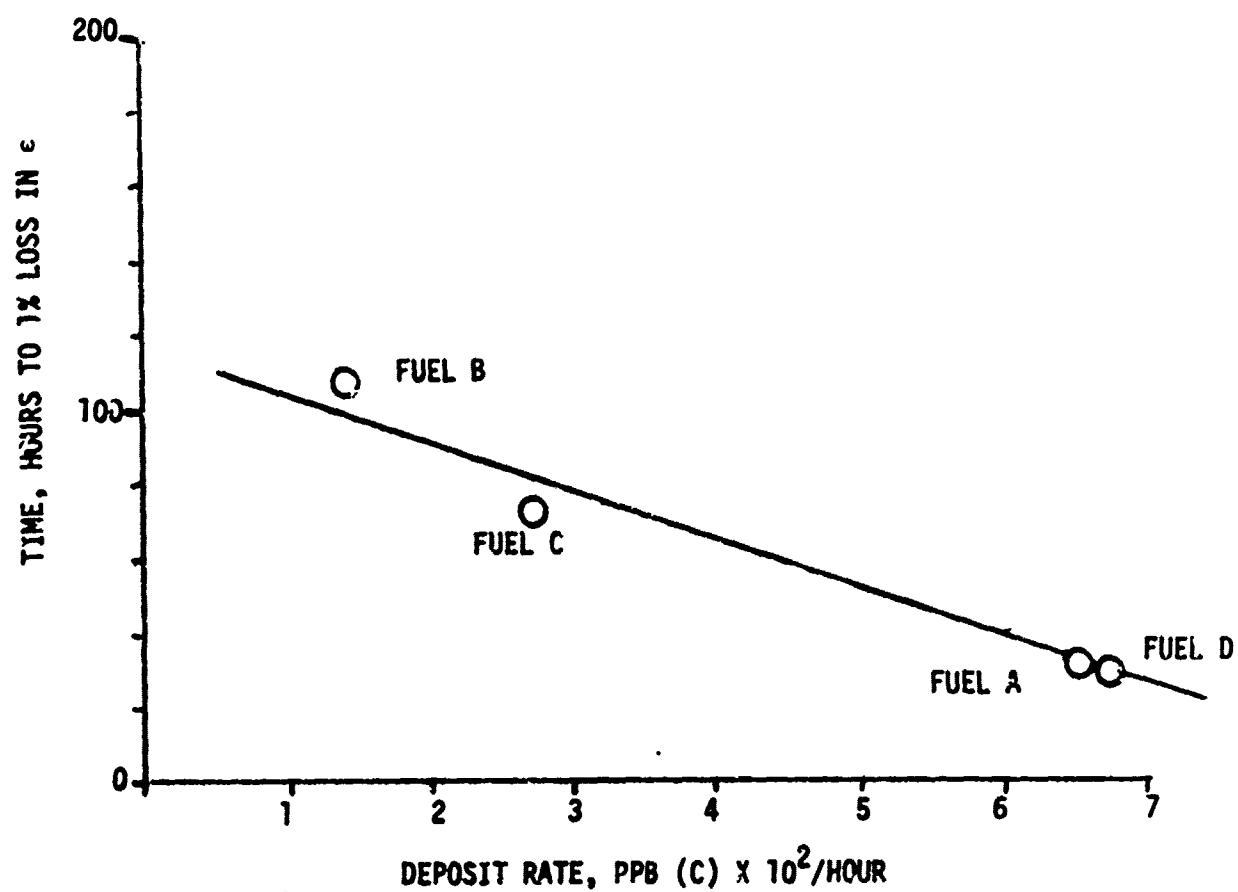


TABLE I  
SUMMARY OF SIGNIFICANT HOT FUEL PERFORMANCE DATA

<u>REGRESSION LINE</u> <u>CORRELATION</u> <u>COEFFICIENT (1)</u>	<u>FUEL</u>	<u>MINIMUM</u> <u>JFTOT BREAKPOINT</u> <u>TEMPERATURE, °C (°F)</u>	<u>MAXIMUM FUEL</u> <u>HX TEMPERATURES,</u> <u>°C (°F)</u>	<u>TIME, HOURS TO</u> <u>1% LOSS IN <math>\epsilon</math></u>	<u>LENGTH OF</u> <u>TEST, HRS</u>
-0.62	A	238 (460)	188 (370)	31	280
-	B (2)	271 (520)	170 (338)	107.3	334
-0.835	C	232 (450)	170 (338)	73	717
-0.728	D	213 (416)	170 (338)	29	360

NOTE: (1) -1.0 would be perfect fit.

(2) Based on data between 266 hours and end of test.

TABLE II

HOT FUEL PERFORMANCE, RATE OF DEPOSITION

<u>FUEL</u>	<u>TOTAL CARBON, MILLIGRAMS (1)</u>	<u>TOTAL CARBON CONCENTRATION, PARTS PER BILLION (PPB)</u>	<u>DEPOSITION RATE, PPD (C) X 10<sup>2</sup>/HR</u>	<u>MINIMUM JFTOT BREAKPOINT TEMPERATURE, °C (°F)</u>
A	8.535	18.2	6.52	238 (460)
B	8.025	8.30 (2)	1.38 (2)	271 (520)
C	22.656	19.5	2.72	232 (450)
D	14.098	24.2	6.72	213 (416)

NOTE: (1) Data obtained by Naval Research Laboratory.

(2) Based on 600 hour test

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REFERENCE

1. AUTHORIZATION: AIRTASK NO. A5365360-052F-6WSL700000 of 15 July 1975.

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